Signatures of TeV Scale Gravity in High Energy Collisions

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Abstract

In TeV scale unification models, gravity propagates in $4+\delta$ dimensions while gauge and matter fields are confined to a four dimensional brane, with gravity becoming strong at the TeV scale. For a such scenario, we study strong gravitational interactions in a effective Schwarzschild geometry. Two distinct regimes appear. For large impact parameters, the ratio $\rho \sim (R_s/r_0)^{1+\delta}$, (with R_s the Schwarzschild radius and r_0 the closest approach to the black hole), is small and the deflection angle χ is proportional to ρ (this is like Rutherford-type scattering). For small impact parameters, the deflection angle χ develops a logarithmic singularity and becomes infinite for $\rho = \rho_{crit} = 2/(3+\delta)$. This singularity is reflected into a strong enhancement of the backward scattering (like a glory-type effect). We suggest as distinctive signature of black hole formation in particle collisions at TeV energies, the observation of backward scattering events and their associated diffractive effects.

The main motivation for introducing new physics comes from the need to provide a unified theory in which two disparate scales, ie the electroweak scale $M_W \sim 100$ GeV and the Planck scale $M_P \sim 10^{19}$ GeV, can coexist (hierarchy problem). A novel approach has been proposed for resolving the hierarchy problem [1]. Specifically, it has been suggested that our four dimensional world is embedded in a higher dimensional space with D dimensions, of which δ dimensions are compactified with a relatively large (of order of mm) radius. While the Standard Model (SM) fields live on the 4-dimensional world (brane), the graviton can propagate freely in the higher dimensional space (bulk).
The fundamental scale M_f of gravity in D dimensions is related to the observed 4-dimensional Newton constant G_N by

$$G_N = \frac{1}{V_\delta} \left(\frac{1}{M_f}\right)^{(2+\delta)} \tag{1}$$

where V_δ is the volume of the extra dimensional space. A sufficiently large V_δ can then reduce the fundamental scale of gravity M_f to TeV energies , which is not too different from M_W, thereby resolving the hierarchy problem.

The prospect of gravity becoming strong at TeV energies, opens the possibility of studying gravity in particle collisions at accessible energies (at present or in the near future). To that respect, salient features of the cosmic ray spectrum (the "knee") have been attributed to gravitational bremsstrahlung [2]. By reproducing the cosmic ray spectrum, the parameters of the low scale gravity can be inferred ($\delta \sim 4$ and $M_f \sim 8$ TeV).
In this letter, we would like to study the interactions among particles, mediated by low scale gravity. The optimum would be to address this issue within a complete quantum gravity theory. But we are lacking this framework. We could turn to pertubative quantum gravity. But we would miss all the essential features of strong gravity we are interested in. Furthermore, perturbative calculations are uncertain, since there is no definite method for summing up the Kaluza-Klein contributions [3]. We prefer to work within an effective approach in which gravity effects are treated classically but non-perturbatively. That is, the effect of particle collisions at TeV energy scale is considered as the scattering of a particle in the effective *curved* background produced by all the others. While our estimates would not be the exact answer, we anticipate that they would reflect the main characteristics of strong gravity effects. Several arguments support this approach. Particle collisions in string theory are, within the eikonal approximation, like the classical scattering of a particle in the effective

gravitational shock wave background created by all the others [15],[16]. For large impact parameters, the shock wave profile is of Aichelburg-Sexl type (point particle source). For intermediate impact parameters, the shock wave profile is different, corresponding to a localized extended source [17]. The shock wave background description is only valid for large or intermediate impact parameters, namely weak gravity limit. The scattering phase shift in the Aichelburg-Sexl background just reproduces the phase shift of the newtonian gravitational tail. For small impact parameters (strong gravity effects) a full black hole background is necessary.

We consider a SM particle moving under the influence of a $(4+\delta)$-dimensional black-hole. The effective metric is [4]

$$ds^2 = f(r)dt^2 - \frac{1}{f(r)}\, dr^2 - r^2(d\theta^2 + \sin^2\theta d\varphi^2) \tag{2}$$

where

$$f(r) = 1 - \left(\frac{R_s}{r}\right)^{1+\delta} \tag{3}$$

$$R_s = \frac{1}{\sqrt{\pi} M_f}\left[\frac{M}{M_f}\,\frac{8\Gamma\left(\frac{\delta+3}{2}\right)}{\delta+2}\right]^{1/(\delta+1)} \tag{4}$$

$M_f \simeq$ TeV is related to G_N by eq (1). For particle collisions, $M = \sqrt{s}$, the center-of-mass energy. A particle impinging upon the black hole at impact parameter b will approach the black hole at a closest distance r_0, related by

$$b^2 = \frac{r_0^2}{1-\rho} \tag{5}$$

with

$$\rho = \left(\frac{R_s}{r_0}\right)^{1+\delta} \tag{6}$$

The deflection angle χ of the particle is given by (details will be reported elsewhere)

$$\chi = 2\Phi_0 - \pi \tag{7}$$

$$\Phi_0 = \int_0^1 \frac{d\omega}{[1-\omega^2-\rho(1-\omega^{3+\delta})]^{1/2}} \tag{8}$$

For large impact parameters, ρ acquires small values. A Taylor expansion in ρ provides then

$$\chi = I(\delta)\rho \tag{9}$$

where $I(\delta)$ is a constant depending solely on δ. Our result is in agreement with the results obtained within pertubative (classical or quantum) gravity. Furthermore, by setting $\delta = 0$ we find the traditional Rutherford formula, or the equivalent formula for pertubative Yang-Mills scattering in 4 dimensions. Small b values give rise to larger values of ρ. We find that with decreasing b, χ increases and there is a critical ρ value where χ becomes infinite. A reasonable approximation of χ for all ρ values is the following

$$\chi = a \ln\left(\frac{1}{1-\rho/\rho_{crit}}\right) \tag{10}$$

with

$$\rho_{crit} = \frac{2}{(3+\delta)} \tag{11}$$

$$a = \rho_{crit}\, I(\delta) \tag{12}$$

The parameter ρ_{crit} has a clear physical meaning. It corresponds to the unstable circular orbit around the black hole. As ρ approachs ρ_{crit}, the particle starts orbiting around the black hole before escaping to infinity. At $\rho = \rho_{crit}$ the particle stays in circular orbit, implying an infinite value for χ. For $\rho < \rho_{crit}$ the particle is fully absorbed by the black hole.
Our findings, transformed into differential cross-section, provide

$$\frac{d\sigma_0}{d\Omega}(\chi) = C R_s^2 \frac{1}{\sin\chi} \frac{\exp(-\chi/a)}{[1-\exp(-\chi/a)]^{\frac{(3+\delta)}{(1-\delta)}}} \tag{13}$$

where C is a δ-dependent constant. Notice that the one-to-one correspondence between the impact parameter b and the deflection angle χ is lost

$$\rho = \rho_{crit} - \rho_{crit}\, e^{-\chi/a} \tag{14}$$

Due to orbiting, different values of b give rise to the same χ. We have to sum over all $\chi_n = \chi + 2n\pi$ and the differential cross section becomes

$$\frac{d\sigma(\chi)}{d\Omega} = \sum_{n=0}^{\infty} \frac{d\sigma_0}{d\Omega}(\chi_n) \tag{15}$$

At small χ, the cross-section diverges like $(1/\chi)^\gamma$ with $\gamma = (4+2\delta)/(1+\delta)$. (for $\delta = 0$, $\gamma = 4$). This is the well known focusing of forward scattering at $\chi = 0$ due to the large range (newtonian or coulombian) interaction at large distances. At large angles, the cross-section, although is relatively suppressed, it diverges again at $\chi = \pi$, like $\frac{1}{(\chi-\pi)}$ for any δ. This focusing at backward scattering is due to the strong attractive black hole potential at

short distances (it is not present in less attractive gravitational fields, nor in Rutherford scattering).

Imagine then collisions of cosmic rays particles in the atmosphere. At very high energies, approaching the fundamental scale of gravity M_f, gravitational interactions become important and it is expected that in some events, backward scattering will occur. Experimental devices like EUSO [5], OWL [6], will register the development of a shower changing direction suddenly. We suggest that this type of events should be seen as evidence for black hole formation in cosmic rays interactions, mediated by TeV scale gravity. Similar situations may arise in detecting high energy neutrinos by a neutrino telescope [7]. The induced energetic muon might spiral and the emitted Cherenkov light will form a luminous halo rather than a forward cone. Again, these events should be classified as black hole formation.
Our calculation reveals another generic feature known as duality [11]. Gravity at large distances behaves like pertubative Yang-Mills fields at short distances, both providing power-law behaviours. On the other hand, gravity at short distances is described by exponential cutoffs, very similar to soft QCD phenomena at large distances. Clearly, this issue desserves further study.

There is an extensive literature on black hole formation in particle collisions, within the framework of low scale gravity [8],[9]. In these works, the detection of the emitted Hawking radiation has been proposed as signal for black hole production. Hawking radiation corresponds to particles just escaping the horizon and in a realistic situation one should include the radiation emitted in the whole scattering process. Furthermore a black-body spectrum for emitted particles is not synonymous of Hawking radiation. In hadronic collisions at high energies the emitted particles follow thermal spectra, without even implying thermal equilibrium [10]. The relevant calculations [8],[9], presssupose also the validity of the parton model. However the formation of a black hole corresponds to the strong gravity regime, with multiple gravitons being exchanged, and the hypothesis of individual "free" partons is not justified.

We anticipate that quantum effects will make milder the $\chi = \pi$ singularity. In analogy to the wave scattering by a black hole [12], [13], [14], diffractive scattering effects should be expected, and interference between the waves scattered at angles differing in 2nπ, (n=1, 2,...) will occur. A pattern of bright and dark rings (equivalent to the "glory" effect rings) will emerge, a distinctive feature of the presence of a black hole state formed in

the collisions. The S-matrix for such collisions should show an oscillatory picture as a function of the scattering angle, with specific location of peaks and dips between the two enhancements at $\chi = 0$ and $\chi = \pi$.

Altogether we analysed gravitational scattering within the TeV-scale gravity models. Our treatment is classical but incorporates all non-perturbative features of strong gravity. We find out that scattering mediated by gravitational interaction develops a singularity at scattering angle $\chi = \pi$. Only a black hole, a compact object associated with a horizon can produce this effect. We suggest then the observation of backward scattering events, associated with rainbow-like diffraction patterns, as signals for the formation of black hole states in high energy particle collisions. Experiments to be carried out in the near future would test the reality of gravity becoming strong at TeV energies.

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